Report for 2004IA64B: Hydrologic Modeling of Subsurface Drainage for Predicting Drainage Outflow

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Report Follows

Hydrologic Modeling of Subsurface Drainage for Predicting Drainage Outflow

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Problem and Research Objectives

Movement of water and nutrients through subsurface drainage systems is a concern in many midwestern agricultural watersheds, including the Des Moines Lobe of Iowa. Although subsurface drainage has its benefits—it improves the productivity of croplands and generally reduces surface water runoff—these systems result in a greater volume of subsurface drainage flow to downstream water bodies, thereby increasing nitrate-nitrogen movement to the same. In order to reduce excess water movement and nitrate-nitrogen movement in these watersheds, hydraulic modifications of drainage systems are being considered as water quality management practices. At the Iowa Water Summit held at Iowa State University on November 24, 2003, three of the five work groups (Nonpoint Sources, Nutrients, and Impaired Water Restoration) identified the need for assessment and demonstration of hydrologic modifications as a new way of addressing water quality concerns, particularly nitrate-nitrogen leaching. Two hydrologic modifications commonly proposed are shallow drain tube installation and controlled drainage. Shallow drainage consists of placing conventional tile drains at shallow depths (e.g., at 24-30" rather than at 48-60"). Controlled drainage raises the outlet of the drainage system at certain times to raise the water table. These modifications to the drainage system are expected to have a direct effect on the volume of subsurface flow and nitrate-nitrogen concentrations and loading from subsurface flow.

However, to evaluate effectively the performance of tile-drained landscapes and potential impacts of modifications, water and nutrient outflow in the system must be accurately estimated or predicted under different scenarios. Use of hydrologic models affords one the opportunity to evaluate the impact of different management strategies on water quantity and quality in subsurface drainage systems; but in order to have confidence in the modeling results, the models should be calibrated and validated. Through calibration and validation the impact of parameters that affect drainage volume—specifically, soil hydraulic properties and climate conditions—can be better understood. With this information in hand, researchers gain confidence in the models' ability to predict subsurface flows and ultimately make use of them in management decisions.

DRAINMOD (Skaggs, 1978) and MIKE SHE (Refsgaard and Storm, 1995) are two hydrologic models that have the ability to model subsurface drained systems. DRAINMOD is a field-scale water management simulation model that uses climate data to predict water table depth, subsurface and surface drainage, evapotranspiration, and seepage on a day-to-day and hour-to-hour basis. In addition, a freezing and thawing component has been developed for DRAINMOD to enhance its use in colder climates (Luo et al., 2000). DRAINMOD has been used successfully under a variety of soil, crop, and weather conditions. MIKE SHE is a deterministic, distributed and physically based model that allows for simulation of all major processes occurring in the land phase of the hydrologic cycle. The model allows for spatially varying precipitation, vegetation, soil hydraulic properties, and land uses. Water movement modeling in MIKE SHE includes overland and channel flow, unsaturated and saturated water flow, interception, and evapotranspiration. Since MIKE SHE is a distributed model, it has the potential to simulate areas with and without tile-drainage; subsurface drainage can be specified for each cell within the model area. MIKE SHE could have the potential to model areas where tile drainage is random, and the pattern drainage, as simulated in DRAINMOD, may not be as applicable. The MIKE SHE model was developed by the Danish Hydraulic Institute, and its use has been limited in the Midwest. However, a recent study at the University of Nebraska found that MIKE SHE performed well in simulating two-dimensional overland flow in a vegetative filter (Helmers et al., 2003).

The modeling associated with this project would allow for evaluation of drainage systems using a long-term data set (1988–present) in a geographic area of importance in subsurface drainage and nitrate-nitrogen leaching (the Des Moines Lobe). In addition to modeling the drainage system, this long-term drainage record allows comparison of annual drainage volume and the temporal subsurface flow patterns from a fifteen-year precipitation and drainage record.

The objectives of this investigation are:

1. to evaluate the ability of DRAINMOD to simulate water flow through subsurface drainage systems;
2. to evaluate the ability of MIKE SHE to simulate water flow through subsurface drainage systems;
3. to evaluate differences in soil hydraulic properties for the different drainage area plots used and the impact of varying levels of site-specific soil-hydraulic-property information on simulated subsurface drainage; and
4. to review a fifteen-year drainage record to investigate the timing and quantity of subsurface drainage.

The hypotheses associated with this work are that DRAINMOD and MIKE SHE can be used to adequately predict drainage outflow, that significant variability in soil hydraulic properties from one plot to the next affect subsurface drainage, and that the accuracy of modeled and measured subsurface drainage is improved with site-specific soil hydraulic properties. This research has applicability in addressing the suitability of models for predicting subsurface drainage and the level of input data required to make accurate predictions. This research is focusing on the drainage outflow, with possible future research in this area to focus on the ability to predict nitrate-nitrogen leaching.

Methodology

In 1988, a research site in Gilmore City, Iowa, was established for studying subsurface drainage from agricultural land. A total of 78 research plots were constructed. Individual plots are 38.1 m long and 15.2 m wide. A 76 mm diameter perforated drain line was buried 1.4 m deep in the center of each plot. Another 76 mm drain line was installed on each side of the plots to prevent subsurface movement of water from one plot to another. The center line tile has been monitored in the plots for flow volume and water quality.

Hourly rainfall and daily maximum and minimum temperature are requirements for the DRAINMOD weather input. Daily rainfall and maximum and minimum temperature were obtained from an on-site weather station. This daily rainfall was distributed over 12 hours within the 24-hour period for the initial modeling with DRAINMOD. Future work will estimate hourly precipitation from the daily amount using the CLIGEN weather generator. There were short periods during the fifteen years when data was not collected with the on-site station so information from nearby stations (Pocahontas and Humboldt, IA) was used.

The Rosetta Model (Schaap, 1999) can produce all the parameters that DRAINMOD requires for soil properties by inputting soil particle distribution. Bulk density, water contents at -0.33 bar and -15 bar are optional input for Rosetta. For the Soil Survey estimation method, as referred to herein, the soil name for each plot was found in the soil map of Soil Survey of Pocahontas (United States Department of Agriculture, Soil Conservation Service, 1985), and the soil texture and bulk density of corresponding soil was determined from the Iowa Soil Properties and Interpretations Database (Version 7.0, 1/03/2004). The water content at -0.33 bar and -15 bar were estimated by graphs developed by Rawls and Brakensiek (1983) when the soil texture is known. For the Soil Texture estimation method, soil samples were extracted from 4 locations in each plot, and for each location, 3 samples were extracted from 3 different depths of 15, 38 and 61 cm. Both data of soil survey and soil test were input into the Rosetta Model; then, the results were input into the DRAINMOD to perform the drainage simulations from 1990–2004. Hydraulic conductivity and the soil-water retention curve are major factors of the soil that affect drainage volume. These data are also being gathered from laboratory testing to estimate plot specific soil hydraulic property information. This data will then also be used for the drainage modeling. This would be termed the Soil Test estimation method. Within the course of this project we will be comparing results from the Soil Survey, Soil Texture, and Soil Test estimation methods.

Rooting depth of the crop is an input parameter within DRAINMOD. Rooting depth of corn in Minnesota, which is included as a default file in DRAINMOD, was selected as the crop data in this case. The maximum Effective Rooting Depth for corn in this case was 30 cm, which is supported by Mengel and Barber (1974).

Principal Findings and Significance

From nearby weather records, the 30-year (1975–2004) average annual precipitation is 820 mm (Table 1) and the 30-year average for the primary drainage season months of April through November is 700 mm. During the fifteen years of this study, both the average annual and average drainage season precipitation were below the 30-year normal. The wettest year at the site was 1991 (918 mm) and the driest year was 1997 (471 mm). The amount of drainage varied significantly from a low of 11 mm in 1997 to a high of 587 mm in 1993. Overall, from the fifteen years, the ratio of drainage to precipitation for the April to November time period was 41% (Table 1). From the fifteen-year project site precipitation record, the greatest precipitation months are April through August (Figure 1). June had the greatest monthly mean precipitation during this period with a mean precipitation of approximately 125 mm. From Table 1, there were large differences in the amount of drainage season precipitation and drainage, and drainage volume also varied with similar precipitation amounts. Years 1999 and 2000 had nearly equal precipitation amounts (560 and 555 mm), but the drainage amounts were dissimilar with 133 mm in 1999 and 15 mm in 2000. The climatic conditions that affect drainage volume include not only amount but also when the precipitation occurred, timing since last precipitation event, and intensity and duration of the event. Despite this, we found a strong correlation in precipitation and drainage for the months of April through November for the study period (Figure 2).

Table 1. Summary of yearly precipitation, drainage, and ratio of drainage to precipitation

	Precipitation (mm)		Drainage (mm)	Drainage Ratio	
Year	Annual	Drainage Season (April–November)	Drainage Season (April–November)	Drainage to Annual Precipitation	Drainage to Drainage Season Precipitation
1990	839	715	353	0.42	0.49
1991	944	776	362	0.38	0.47
1992	815	656	386	0.47	0.59
1993	942	787	587	0.62	0.75
1994	656	528	21	0.03	0.04
1995	721	600	268	0.37	0.45
1996	763	651	465	0.61	0.71
1997	525	421	11	0.02	0.03
1998	708	592	243	0.34	0.41
1999	675	560	133	0.20	0.24
2000	687	555	15	0.02	0.03
2001	702	600	278	0.40	0.46
2002	680	651	237	0.35	0.36
2003	684	599	439	0.64	0.73
2004	767	610	235	0.31	0.39
Avg.	741	620	269	0.35	0.41
30-yr Normal	820	700			

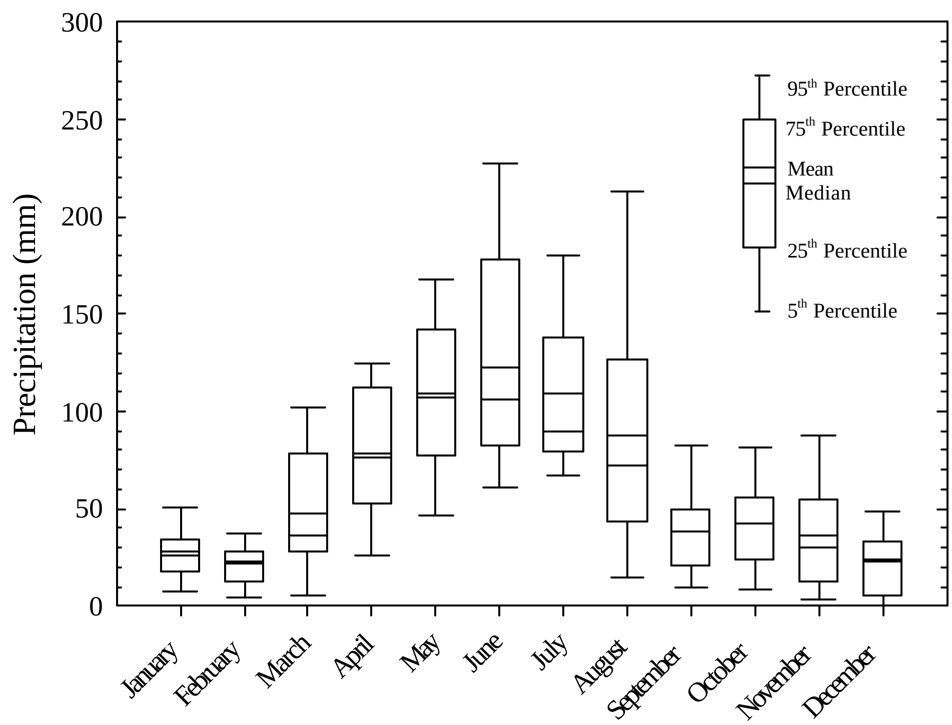

Figure 1. Distribution of monthly precipitation at the project site

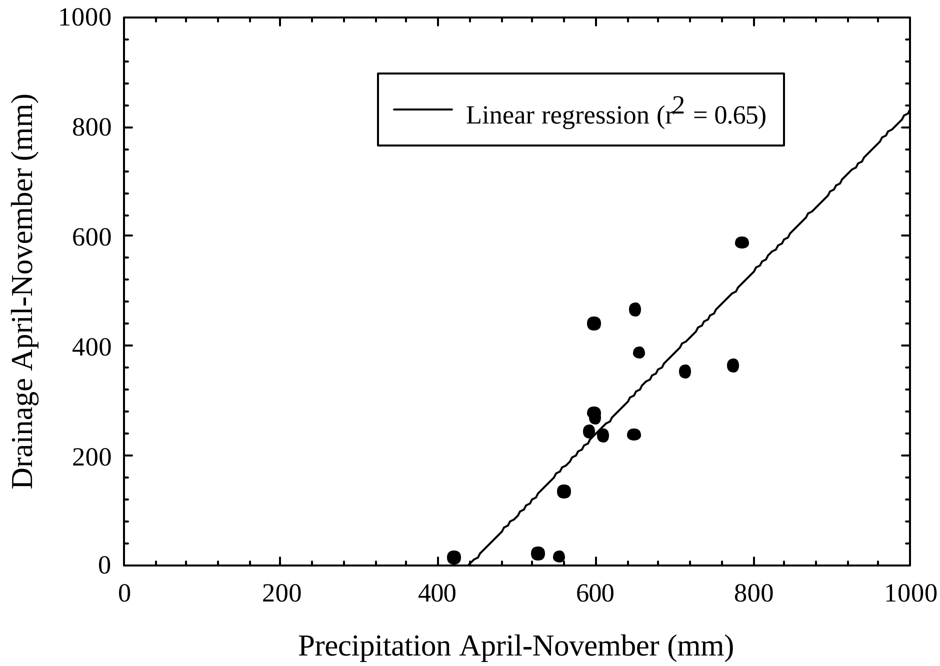

Figure 2. Correlation of precipitation and drainage (April–November)

From the monthly precipitation, it is evident that the rainfall is not uniformly distributed throughout the year; spring and summer months have greater precipitation than late fall and winter. A review of the precipitation and drainage data during the predominant drainage season (April–November) indicated that October was the driest drainage month with 6% of the drainage season rainfall and only 1% of the total season drainage (Figures 3a and 3b). Approximately 50% of the drainage season precipitation occurs in April, May, and June, resulting in 70% of the total drainage observed. The wettest of these three was June with 20% of the rainfall and 31% of the drainage. On average, there is rainfall in September, October, and November but little drainage. This is likely a result of the rainfall recharging the soil profile after the soil moisture was depleted by the growing season. As discussed above, on average, there is little drainage in the months of August, September, October, and November. While the significant drainage periods from April through June correspond with periods of significant rain, most of this time also coincides with periods without much vegetative growth. The ratio of drainage to precipitation is greater in April, May, and June than any of the other months (Figure 4).

The time periods of greatest drainage also correspond to a time of the year when drainage is essential to maintain trafficability, crop germination, and early crop development. So, including drainage management practices that may manage outflow during certain times of year would need to be considered carefully so they are effective in reducing drainage volume while also ensuring adequate drainage capacity to reduce any potential negative effects of drainage management on crop production. Likewise, a wetland downstream from a drainage system would need to be sized and designed to accommodate most of the drainage water entering the system in a three-month time span on average. Since there is little water use during the time period of April through mid-June, any excess rainfall and soluble pollutants within the soil profile are susceptible to leaching. Methods to promote more water use during this time may have positive impacts on reducing drainage volume and subsequent loss of pollutants. For instance, a crop system that includes vegetation which could remove excess precipitation via transpiration in April and May could significantly reduce drainage volumes while not adversely affecting soil moisture since much of the precipitation is lost to drainage in these months.

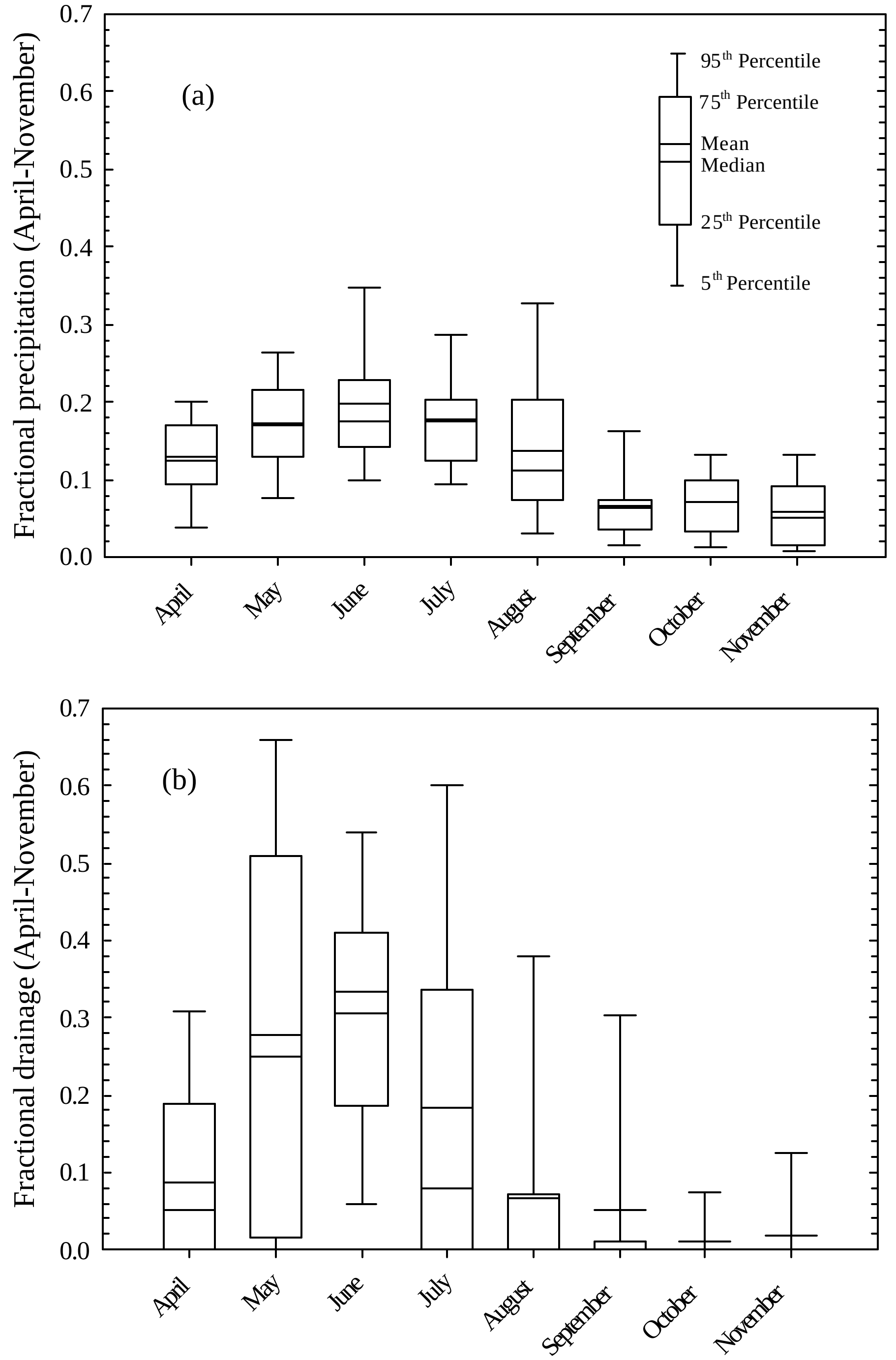

Figure 3. Box plot diagrams of monthly fraction of drainage season (a) precipitation and (b) drainage

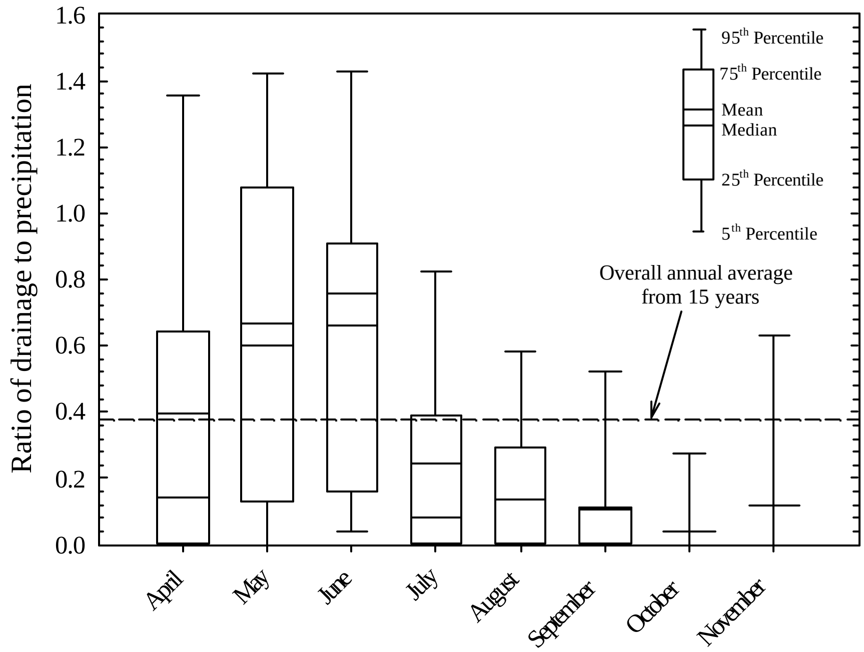

Figure 4. Ratio of monthly drainage to monthly precipitation

DRAINMOD simulations have been performed for the study plots using Soil Survey input data for soil properties as well as Soil Texture input from soil samples gathered at the project site. Cumulative drainage flow, both measured and simulated, for three of the representative plots is shown in Figures 5, 6, and 7. Again, these simulations were performed using two levels of soil input information—Soil Survey and Soil Texture—and were performed without calibration of the model. Of note from these initial simulations is that the estimated evapotranspiration and crop rooting depth were found to have a relatively significant impact on simulated drain flow. From these initial results, the model seems to perform relatively well in simulating drain flow from some of the plots, but additional work is required to explain some of the discrepancies evident when comparing measured and simulated outflow. For plots 19-3 and 6-1, the measured and simulated cumulative drainage for the fifteen-year period differed by 7 and 10%, respectively. The simulated cumulative drainage for plot 17-2 was 65% greater than the measured drainage. There was little difference between the simulated results using either the Soil Survey or Soil Texture input parameters for soil hydraulic properties (Figures 6, 7, and 8).

While DRAINMOD performed relatively well in predicting drainage outflow for some of the plots simulated as part of this study, future work on this project will focus on developing site-specific soil hydraulic property input data. In addition, the estimates of rooting depth and potential evapotranspiration will be reviewed relative to values reported in the literature to ensure the most appropriate estimates are used in the modeling. Once this information is finalized, the model will be calibrated to assess calibrated values of evapotranspiration and rooting depth along with the variability of calibrated values for soil parameters. Future work will also involve using MIKE SHE to assess its ability to simulate subsurface drainage. Since this is a spatially explicit model, this component of the project could prove important for future projects because, if the model proves accurate and useful in the tile-drained landscape, it could be used to investigate watershed scale impacts of subsurface drainage where areas with and without subsurface drainage can be simulated. Reliable models and parameterization of these models for subsurface drainage have great significance for understanding agricultural water quality because, while subsurface drainage is essential for agricultural production in many areas and in many cases can reduce surface water runoff and pollutant loss via surface water runoff, subsurface drainage contributes to nitrate loss and movement of nitrate to downstream surface water bodies.

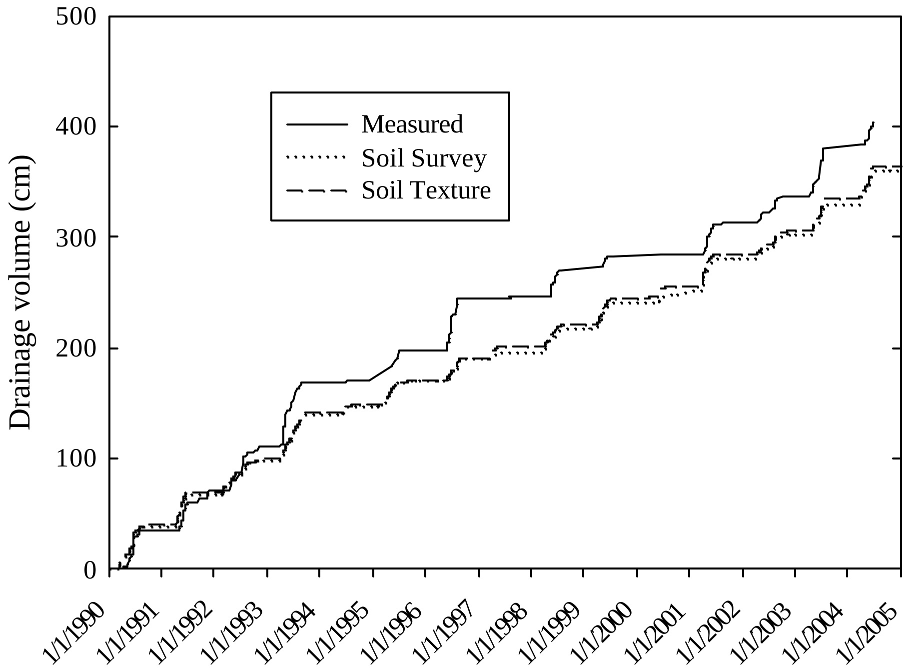

Figure 5. Comparison of measured and simulated drainage from plot 6-1 (simulations used soil properties from Soil Survey data or Soil Texture data)

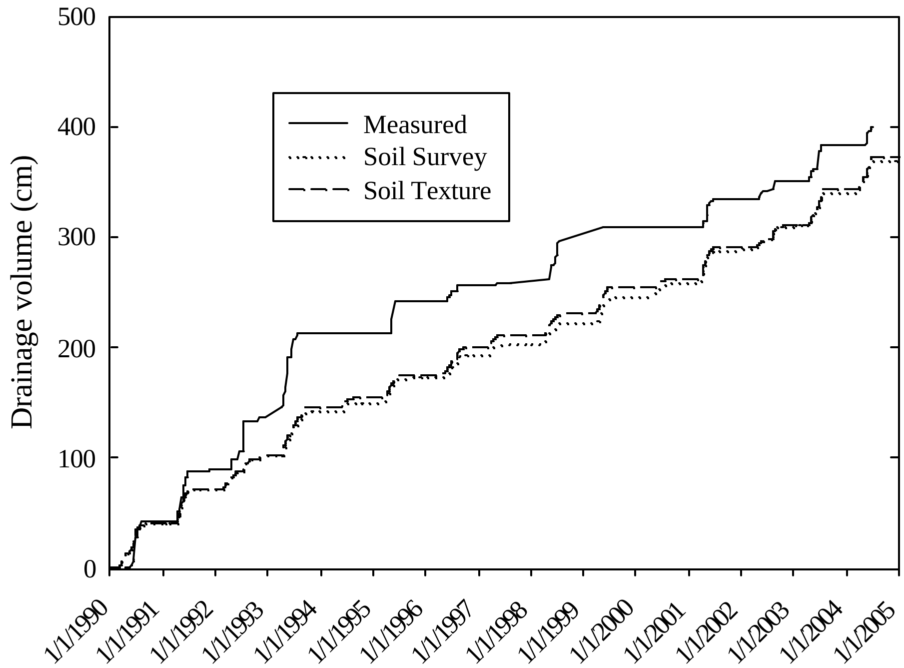

Figure 6. Comparison of measured and simulated drainage from plot 19-3 (simulations used soil properties from Soil Survey data or Soil Texture data)

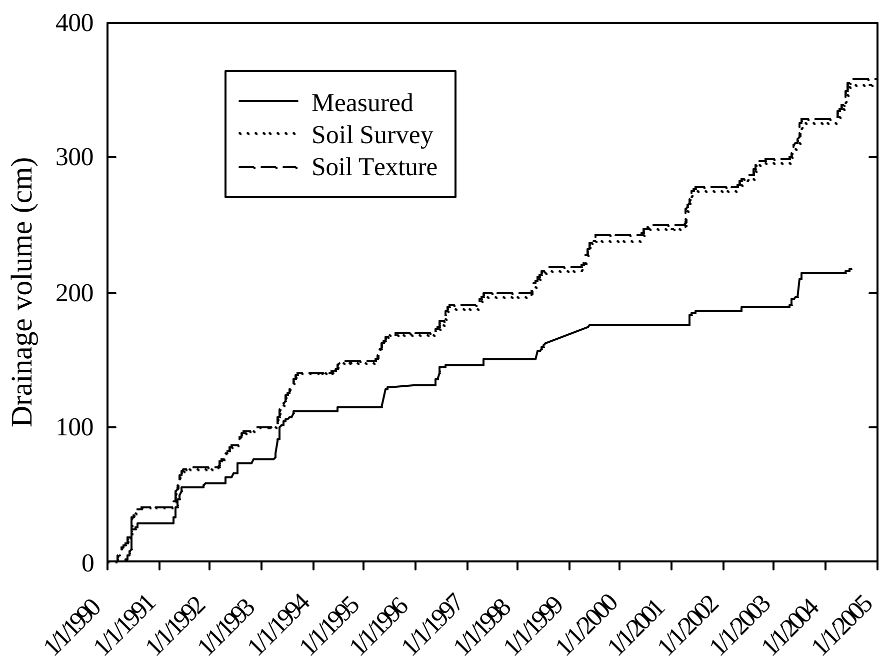

Figure 7. Comparison of measured and simulated drainage from plot 17-2 (simulations used soil properties from Soil Survey data or Soil Texture data)

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